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Burners for Supersonic Ramjets - Some Observations on Instability in a Two-Inch Ramjet Burner (Bumblebee Report)

(None)

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An experimental study of instability and rough burning in a 2-in. ramjet burner was carried out. The findings were correlated with various observations in connection with both the development of ramjet burners and general combustion research. Three types of pressure fluctuations were differentiated and defined in terms of their frequencies. In each type a mechanism was proposed which predicts the occurrences and frequency of these fluctuations with reasonable accuracy.

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EXPERIMENT INCORPORATED
DEEPWATER TERMINAL ROAD
RICHMOND, VIRGINIA
Operating Under Contract NOrd 9756
With the Bureau of Ordnance, U. S. Navy

BURNERS FOR SUPERSONIC RAMJETS

Some Observations on Instability In A Two-Inch Ramjet Burner

By

J. B. FENN — H. B. FORNEY — R. C. GARMON

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Report No. 119
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BURNERS
FOR
SUPERSONIC RAM-JETS

Some observations on instability in a two-inch ramjet burner

J.B. FENN

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BUMBLEBEE REPORT NO. 119

JANUARY, 1950

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SUMMARY

An experimental study of instability and rough burning in a two inch ram-jet burner has been carried out. The findings have been correlated with various observations in connection with both the development of ram-jet burners and general combustion research.

Three types of pressure fluctuations have been differentiated and defined in terms of their frequencies. In each type a mechanism has been proposed which predicts the occurrence and frequency of these fluctuations with reasonable accuracy.

INTRODUCTION

Since the inception of intensive study of high-output ducted burners in connection with the development of ramjet propulsion, it has been the common experience of practically all workers in the field that under certain conditions the combustion process is unstable. The symptoms of this instability have been various including in general the following to a greater or less degree:

1. Marked increase in burner noise.
2. Marked decrease in thrust or efficiency.
3. Pressure fluctuations in the burner of constant or varying frequency and amplitude.

Frequently, the pressure fluctuations become so violent that they culminate in extinction of the burner or actual destruction of its component parts.

Unfortunately, the conditions necessary and sufficient for the onset of burner instability have never been adequately defined or described. This is due partly to the complexity of the phenomenon and partly to the fact that certain empirical developments in burner design have succeeded in eliminating this instability to the extent that it no longer comprises an immediate threat to the successful operation of at least some ramjets. As a result, all burner instabilities have been more or less lumped together and classified by the descriptive but none-the-less vague term, "rough burning." On the other hand, the term "smooth burning" has come to connote that which is desirable in the performance of a satisfactory burner. Moreover, there has been a tendency to discard or ignore burners which are "rough" and to devote the bulk of attention and enterprise toward the development of burners which have demonstrated themselves capable of smooth burning.

Believing that in the long run successful and intelligent burner development and design will depend, among other things, on an understanding of the causes and effects of burner instability, this laboratory has devoted considerable time to a study of rough burning as observed in a two inch ducted burner. The present report is an attempt to summarize the work which has been carried out off and on over the last two or three years. No brief is held for the generality or the applicability to other burners of the results which have been obtained. However, it is hoped that some clues to an understanding of the phenomenon in general will be recorded.

EXPERIMENTAL PROCEDURES

A description of the general features of the two inch burner facility has already been reported together with a discussion of the methods and techniques used in the measurement of the variables associated with the performance of a burner (16). In connection with the investigation of rough burning, however, an additional measurement technique was used. This comprised the determination of the static pressure fluctuations with respect to frequency and amplitude. Both crystal and inductance-bridge type gauges were employed together with appropriate amplifying and recording equipment. These devices have also been previously described (6). The remainder of the experimental details will be elucidated at pertinent points in the following discussion. As a matter of convenience, Figures 1-4 are included here to show the various burner components and their configuration in assembly.

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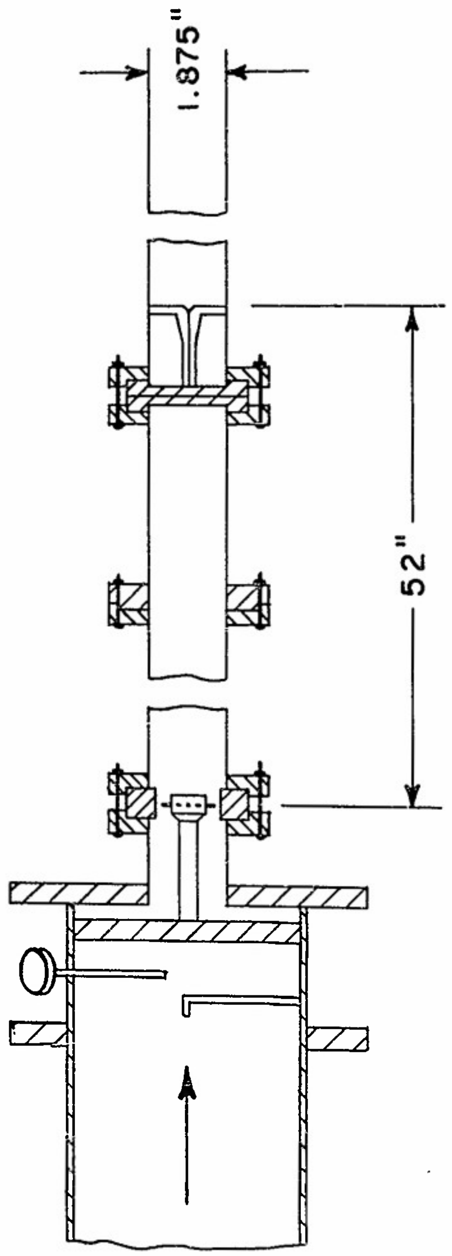

SCHEMATIC DIAGRAM OF BURNER ASSEMBLY

FIGURE I

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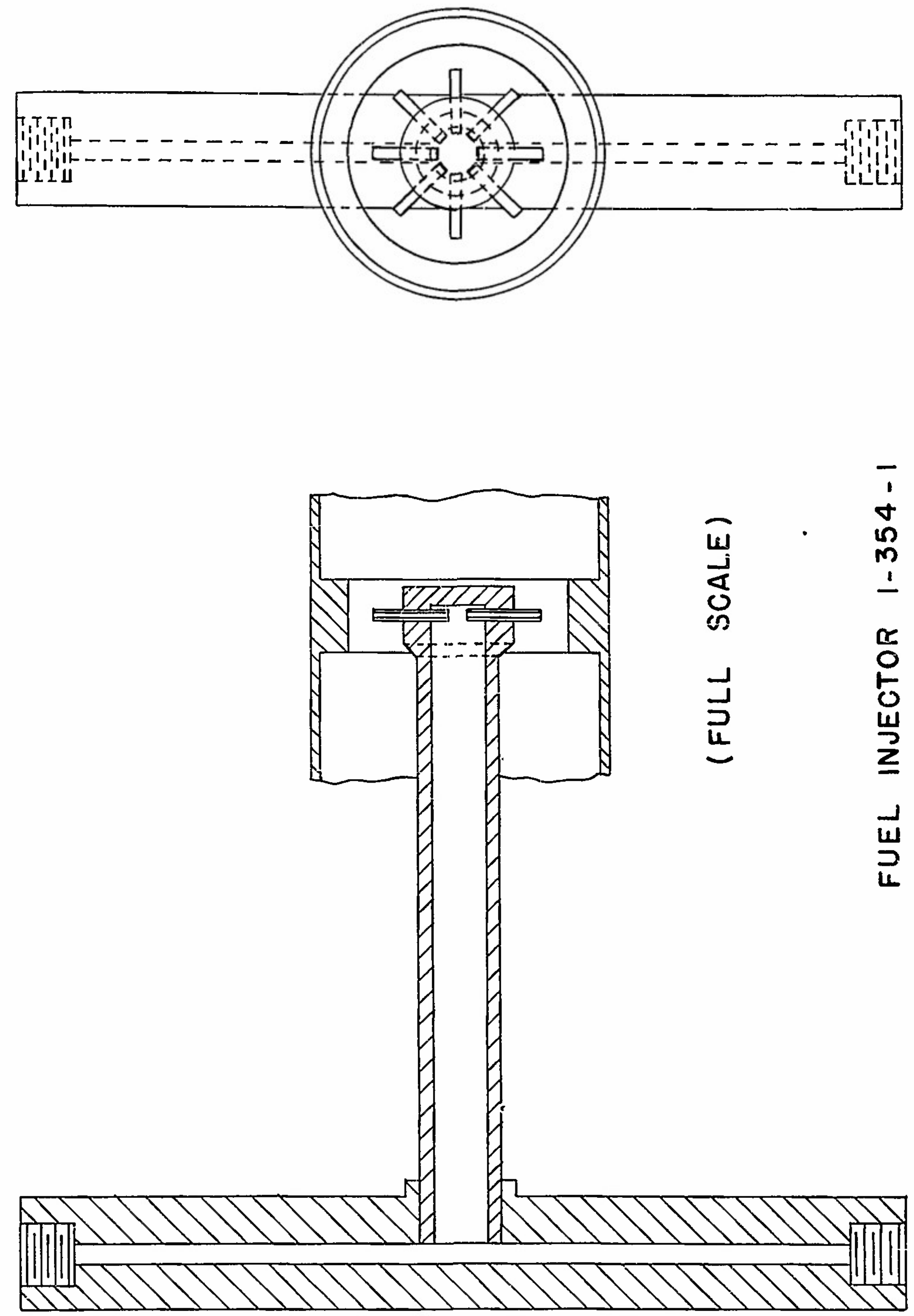
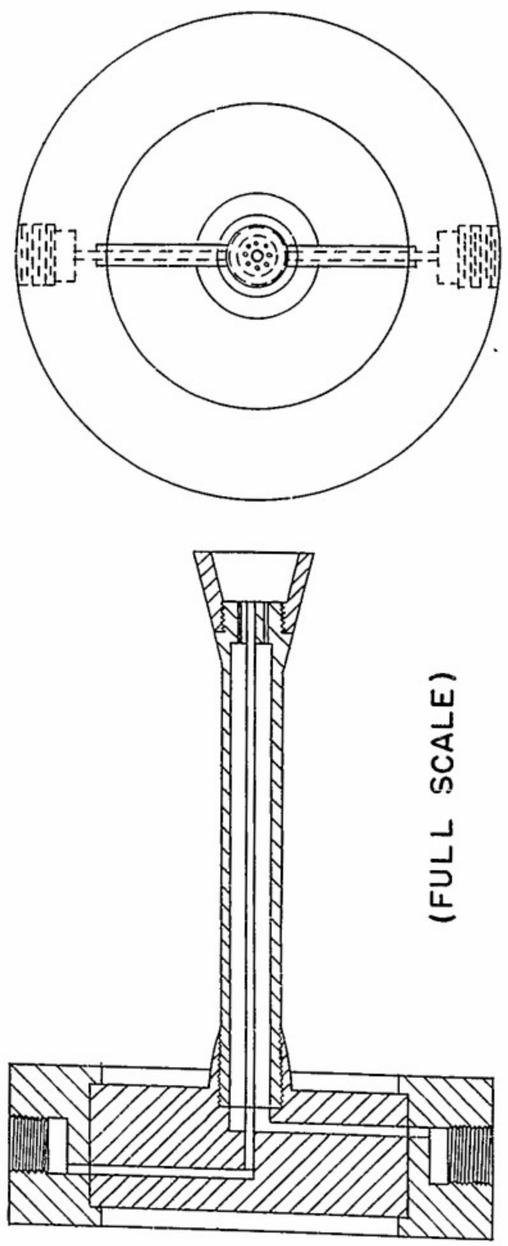


FUEL INJECTOR I-354-I

(FULL SCALE)

FIGURE 2



(FULL SCALE)

IGNITOR 1-2-B

FIGURE 3

DISCUSSION

PART I

As has already been indicated, combustion instability known as rough burning was encountered from the very beginning of the development of ramjet burners. However, because experience with ramjet burners and their behaviour was so limited and because of the urgency to develop a successful burner quickly, no particular study was devoted to the phenomenon itself.

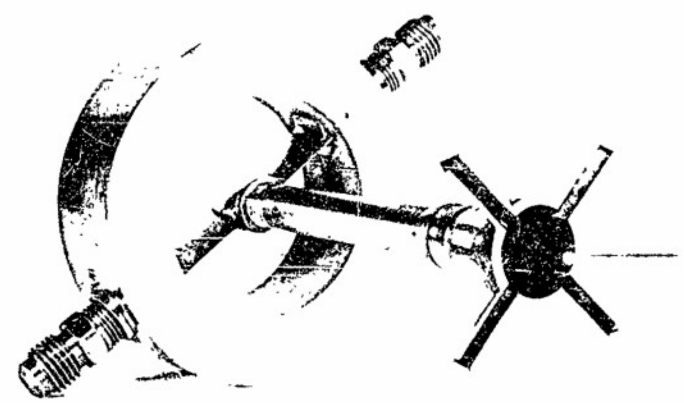


Fig. 4

Rather, it was recognized as something to be avoided. As a result of considerable empirical research of a trial and error nature, some burner configurations were developed which were reasonably immune to instability over a range of operating conditions. Nevertheless, during the course of this early development, a certain amount of intuition concerning the phenomenon was accumulated and some general observations were made. Some of these observations have already been reported (15) but are repeated here as a matter of record.

In the first place, it was noted that ordinarily a burner configuration which was capable of high efficiency was much less susceptible to rough burning than one which could not achieve high impulse or combustion efficiencies. This generality applies only to burners operating with premixed and vaporized air-fuel streams. For example, a burner comprising a simple 0.75" oxyhydrogen pilot cone (Igniter 1-2, Figure 3) is much more prone to instability than one comprising the same cone with the addition of four radial gutters (Igniter 1-226A-B, Figure 4). Correspondingly, with a 14" tailpipe and comparable inlet conditions the former attains an impulse efficiency of 68% as contrasted with 90% in the latter case (16). It should also be noted that although by increasing the tailpipe length the impulse efficiency obtainable with Igniter 1-2 could be greatly increased, the tendency toward rough burning was not decreased. In brief, the instability seems to be associated with the performance of the igniter itself rather than with the overall performance of the burner.

In this same connection it was early observed in the case of piloted burners that the tendency toward rough burning was increased as the amount of heat input by the piloting device was decreased (12). Moreover, a sudden susceptibility of an ordinarily smooth burner to roughness not infrequently was traced to failure of pilot heat input occasioned by leaks in the pilot fuel feed lines.

Both of the above observations seemed to indicate that inadequate ignition was responsible for at least one type of burner instability. Consequently, an explanation was proposed which attributed roughness to the explosion of pockets of air fuel mixture which were not immediately burned due to inadequate primary ignition but which were activated due to pre-flame re-

actions brought about by partial heating from the pilot source (3, 12). These pockets upon coming in contact with the flame front or a hot wall surface burst into explosive combustion which then developed in backfires and detonations. As a matter of fact, rough burning of the most violent type was in general accompanied by the appearance of flame upstream from the igniter (4,5,11). This upstream combustion will be discussed in more detail presently.

It was only natural that the concept of inadequate ignition with resulting pockets of activated but unburned mixture should lead to the proposal that formation of such pockets be precluded by confining the addition of fuel to regions where vigorous burning already obtained. Several burner configurations were thus developed based upon injection of fuel downstream from the igniter into the primary flame (13, 14, 20). This was frequently done in stages, the flame from the first stage acting as a strong pilot for the next stage so that the full flame was developed gradually along the combustion chamber. Although such burners, for a given combustion chamber length, failed to develop efficiencies as high as those obtained with premixed air and fuel, it is noteworthy here that they were invariably quite smooth in their operation.

It was mentioned above that violent rough burning was generally accompanied by the appearance of flame upstream from the igniter or pilot. This was substantiated visually and photographically by the insertion of a glass section in the duct. Figure 5 shows enlarged frames (non-consecutive) from a typical movie sequence which illustrates the appearance of upstream burning. As may be inferred from the pictures, burning upstream is not a steady combustion but rather a series of bursts. It was determined that the distance upstream to which these bursts propagated varied from as little as 4

MOTION PICTURE SELECTIONS - 64 FRAMES PER SECOND

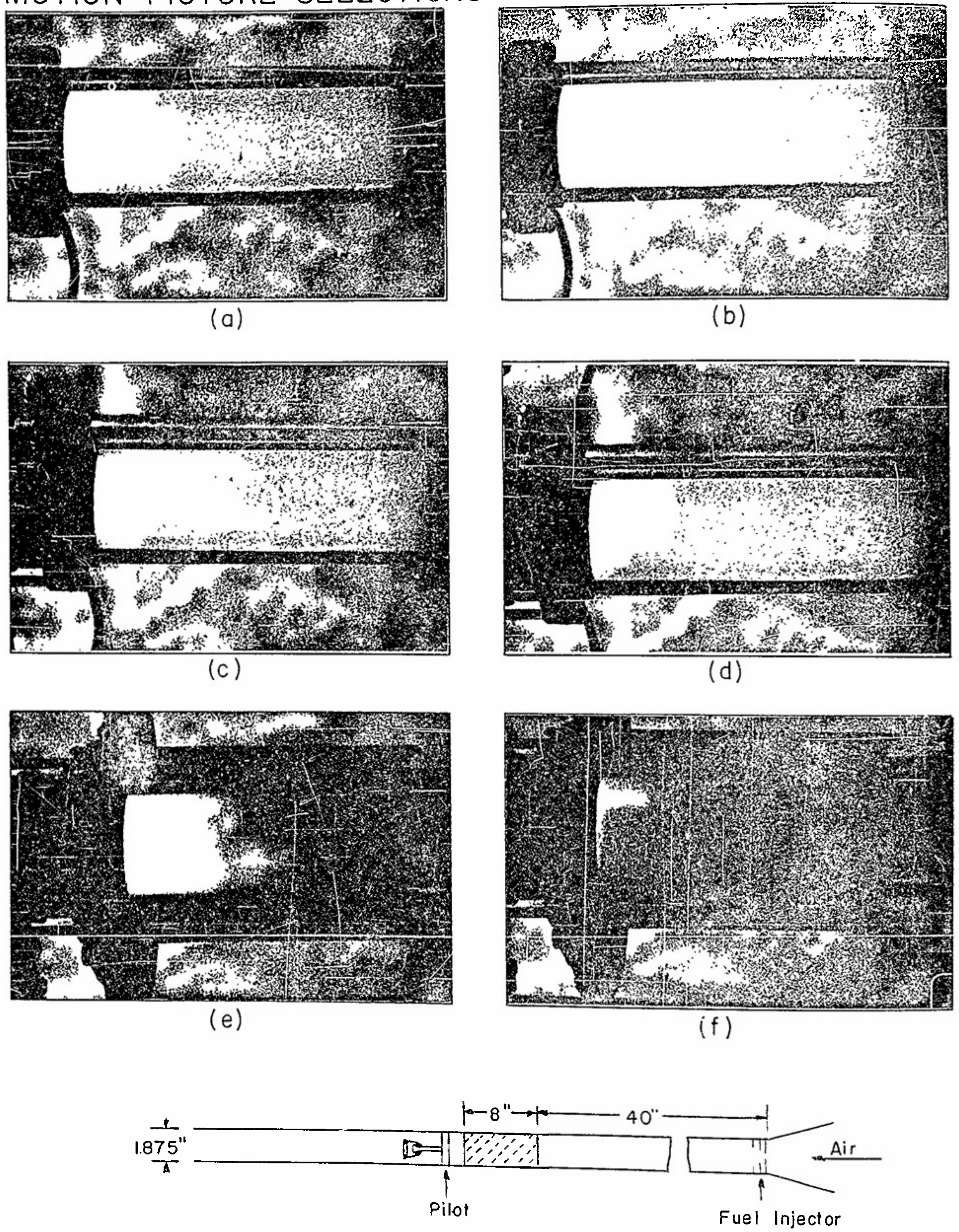


FIGURE 5

to as much as 30 inches upstream from the igniter. No definite evidence was obtained concerning the factor which limited the distance of propagation. However, it is likely that the degree of homogeneity of the air-fuel mixture was important.

Because normal flame velocities for air hydrocarbon mixtures are of the order of a few feet per second, the very existence of flame upstream from the igniter in a stream with a minimum velocity of the order of 200 feet per second indicated propagation rates considerably higher than can be accounted for in terms of ordinary flame propagation. Accordingly, it was decided to measure the rate of propagation. It was soon found that the velocities were beyond those capable of ready measurement by photographic methods because the light intensity of the flame was not sufficient to register at the required film speeds. Moreover, photographic methods require the use of glass sections or windows which are all too easily shattered to be convenient in the study of sustained roughness. Consequently, a method was developed which was based on measuring the time interval between the ionization by the flame of two sets of charged probes a known distance apart. This work has been previously described (8, 10). Suffice it to say that the velocity relative to the duct was found to be of the order of 500 feet per second about 5 inches upstream from the igniter and as much as 3000 feet per second at a distance 24 inches above the igniter. It seems, therefore, that the presence of the flame upstream from the igniter results from true detonation or possibly a quasidetonation as described by Payman and Shepherd (18). While true detonation in the case of paraffinic hydrocarbons is generally observed in oxygen-fuel mixtures, instances have been reported for air-fuel combinations under certain conditions of temperature and pressure (22). The fact that the velocity is lower immediately upstream from the igniter is probably associated with the transition between ordinary propagation and detonation, the latter not being fully developed until some distance has been traversed (2, 17). Incidentally, the existence of a transient regime prior to the development of true detonation was substantiated by the damage done to the probes. They were badly bent when placed 24 inches upstream but not affected when placed 5 inches upstream. Moreover, carbon was found on the walls of the duct, a phenomenon usually associated with the detonation type of combustion.

It next became of interest to see if the locus of the initiation of the detonations could be determined. Two approaches were employed. One involved the use of high speed motion pictures taken with an 8mm. Western Electric Fastax Camera. A glass section was inserted in the duct just downstream from the pilot and exposures were made up to about 1000 frames per second. This speed was not sufficient to resolve the development of a detonation since it appeared from a study of a number of rolls of film that a detonation developed completely in the interval between one frame and the next. At higher film speeds, no images were obtained. In several instances, however, pairs of successive frames were noted in which the first one showed some evidence of the beginning of a detonation at the wall, the next frame being completely bleached as if by a fully developed backfire. Figure 6 shows typical examples of the first frame. The direction of flow is from right to left. It is of interest to note that the location of the two outer streaks is approximately at the intersection of the normal flame front with the duct wall. The central streak is immediately downstream from the igniter, in this case a simple 0.75" cone. In this connection it is of interest that schlieren photographs by Nicholson and Field of a two dimensional analog to the burner used here show a high turbulence together with numerous

MOTION PICTURE SELECTIONS-1000 FRAMES/SECOND

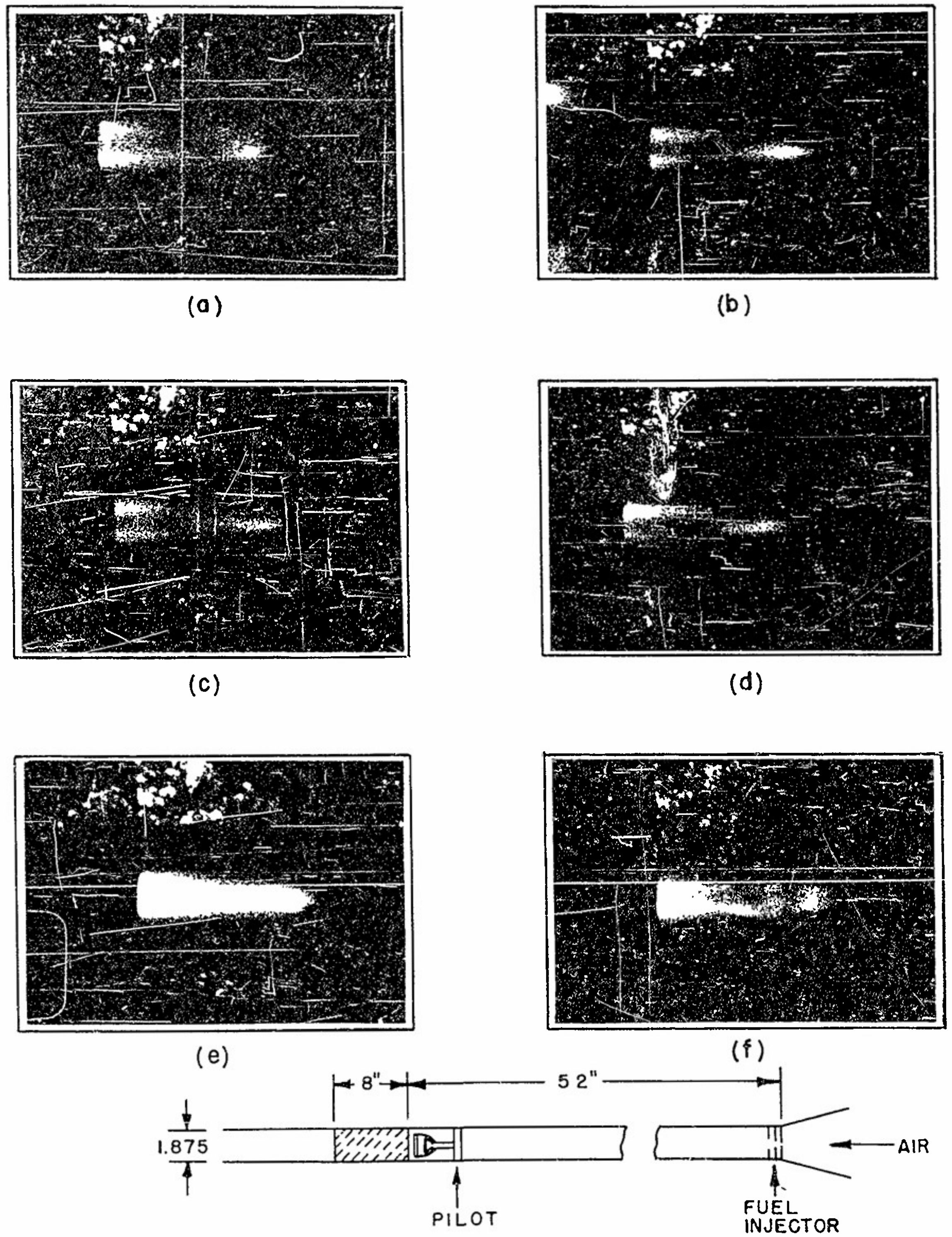


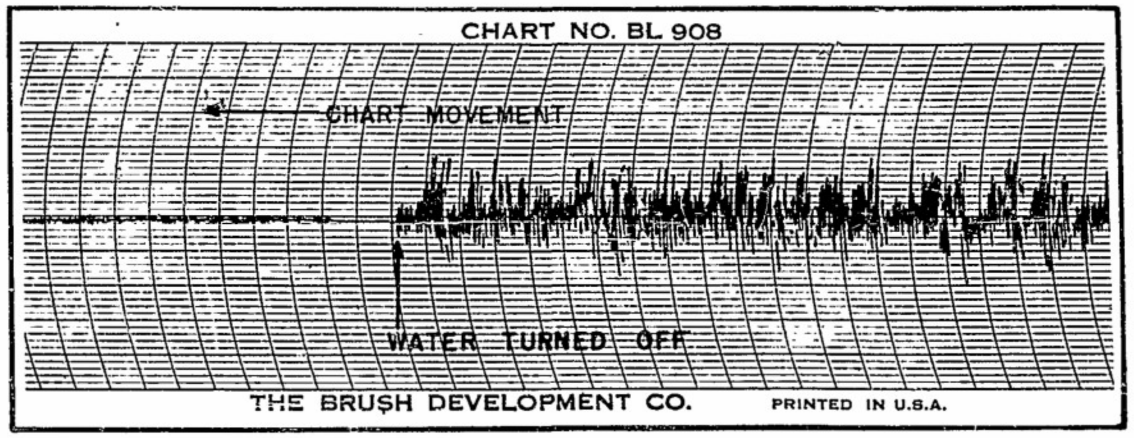
FIGURE 6

shock waves in the region near where the flame front first makes contact with the duct wall (17). Although these photographs were taken under flow conditions differing from those in the burner discussed here, they at least indicate that vigorous mixing and pressure gradients sufficient to trigger a detonation might be expected.

The other approach to the determination of the locus of detonation initiation arose from an observation that injection of fuel near the duct wall sometimes appeared to cause rough burning. It was also observed that a burner with a tailpipe such that the exhaust end nearly coincided with the point at which the normal flame from the 0.75" cone pilot reached the wall was rough when the flame front touched the wall but not when the front was not in contact with the wall. These observations, in view of the fact that the stream velocity was lowest at the wall, thus providing a region for abnormal upstream flames to start, indicated that perhaps detonations did start at or near the wall. It also seemed reasonable that if such incipient detonations could be extinguished at their origin that rough burning might be stopped. Consequently, a brass ring was made up with an inside diameter the same as the duct and which had 0.016 holes at 0.25 inch intervals around the circumference. These holes all opened into an annular chamber within the body of the ring which could be supplied with water under pressure. Thus a film of water could be deposited around the inside of the duct wall. This ring was inserted just upstream from the igniter. It was found that rough burning could be completely eliminated when the water was turned on (3). Moreover, the amount of water required to eliminate the instability was critical. Below a certain flow rate no effect was noted. At about the time of these experiments, the equipment for measuring the frequency and amplitude of the pressure fluctuations associated with rough burning was introduced. Figure

FLUCTUATIONS IN STATIC PRESSURE

EFFECT OF WATER INJECTION IN BOUNDARY LAYER



WATER OFF (ROUGH)

P_2 av ~ 36 psi
ΔP_2 max ~ 34 psi
APPARENT ΔP FREQUENCY, 45 cps

WATER ON (SMOOTH)

P_2 av ~ 44 psi
ΔP_2 av ~ 0.5 psi
ΔP_2 max ~ 3.0 psi

FIGURE 7

7 shows a typical record of the difference between the pressure fluctuations in a rough burner before and after deposition of the water film on the duct wall. A few experiments in other laboratories with larger burners in an attempt to verify the effect of water injection gave inconclusive results and were not pursued to completion. Some evidence of smoothing was noted, however, in a six inch burner when water was injected along the boundary layer (24).

The amount of water required to make the burning smooth was dependent upon the location of the ring (5). Figure 8 shows a plot of the amount of water required to stop roughness versus the position of the ring with respect to the igniter. In this connection it is interesting to note that at any position more than 8 inches downstream from the igniter the burner could not be made smooth no matter how much water was injected. This distance (i.e. 8 inches) also corresponds roughly to the point at which the flame front first makes contact with the wall. One anomaly which was observed comprised the fact that the locus of the injection ring for a minimum amount of injectant required varied with different fuels. The results portrayed in Figure 8 were obtained with heptane. With pentane as fuel, the optimum point of injection occurred 4 inches upstream from the igniter. The reasons for this difference are not immediately obvious. Figure 9 shows the amount of injectant required as a function of the position of the injection ring with respect to the igniter in the case of pentane. It should be pointed out that even much larger quantities of water injected into the stream proper had no effect on rough burning. This was true irrespective of whether the point of injection was well upstream or in the vicinity of the igniter. Consequently, it appeared that the effect of the presence of water was very specific to a location near the junction of the flame front with the duct wall.

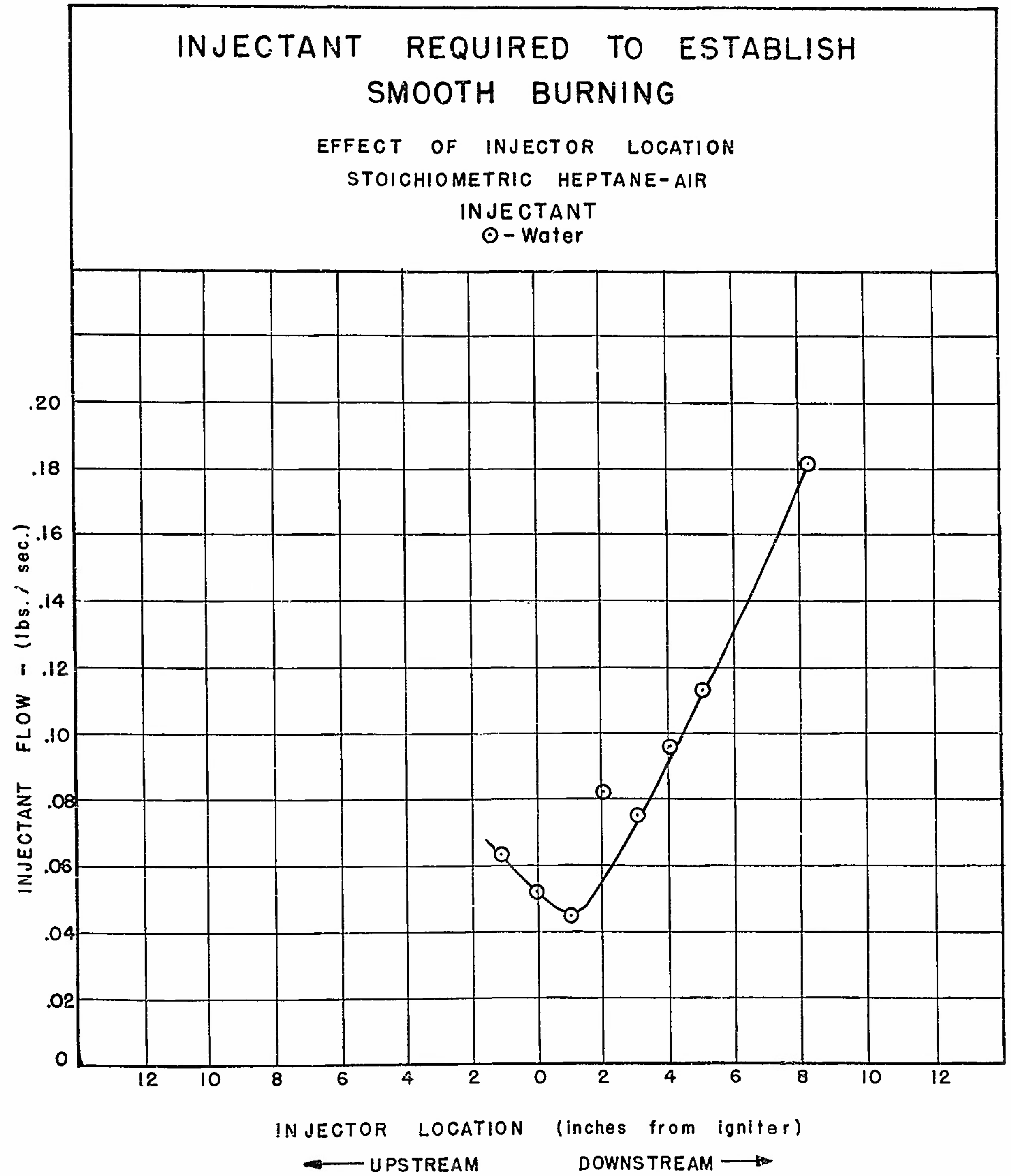


FIGURE 8

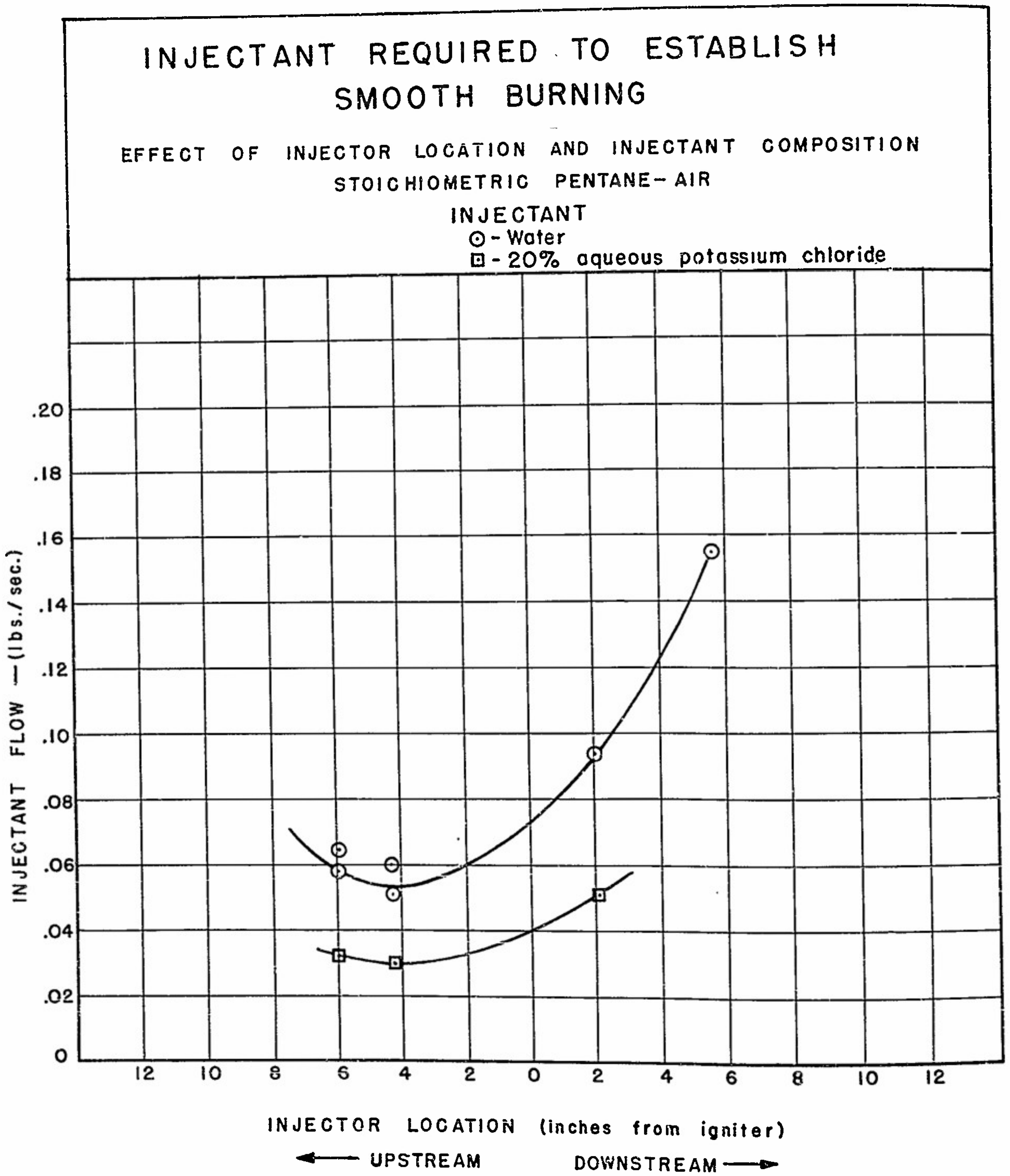


FIGURE 9

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After the effectiveness of so-called boundary layer injection of water had been established by numerous experiments, some thought was given to a mechanism to account for the phenomenon. Assuming that the presence of water in or near the boundary layer at the junction of the flame front with the duct wall prevented the development of backfires, it appeared that such prevention must be due either to simple sweeping out or displacement of the reactive mixture, to quenching, in the sense of abruptly lowering the temperature and therefore stopping the reaction, or to a chemical effect, e.g. destruction of reaction chains or chain carriers. Perhaps a combination of these might be involved. In order to elucidate these possibilities several experiments were carried out which deserve mention.

In the first place a burner was constructed with a jacketed tailpipe through which water could be circulated in order to keep the temperature down. This expedient proved to have no effect whatsoever upon rough burning. Although not conclusive, because of the temperature gradient across the thickness of the duct wall, it did suggest that the smoothing effect of water when injected along the boundary layer was not due entirely to simple cooling.

If, on the other hand, simple displacement of reactive mixture from the specific area was the basic mechamism, it would appear that other materials besides water should be effective. Accordingly, a variety of non-aqueous substances was tried including carbon tetrachloride, aniline, heptane, carbon dioxide, air, and nitrogen. The liquids were injected by means of the ring described above. The gases were introduced by means of a similar ring in which the holes were replaced by a slot around the inner periphery. In each case injection occurred at the point where water had shown the maximum effect. In no case was any smoothing effect observed even though the rate of injectant flow was as high or higher than for water. It therefore did not seem likely that simple displacement of reactive mixture was a sufficient explanation.

The results of the above experiments thus indicated that some sort of chemical effect was probably involved in the smoothing process. Because other workers, e.g. Pease (19), have shown that certain salts such as potassium chloride have a very definite chain breaking effect when present on surfaces in the vicinity of combustion, various salt solutions were tried as injectants. These included sodium chloride, potassium chloride, calcium chloride, ammonium hydroxide, trisodium phosphate, potassium permanganate, and potassium nitrate. Of these sodium and potassium chloride solutions showed a marked improvement over water alone. Figure 9 shows comparative curves for water and 20% potassium chloride solution. An additional experiment was run in which the inside of the tailpipe was coated with a film of sodium silicate-potassium chloride solution and allowed to dry, but no effect on rough burning was noted.

In addition to providing evidence as to the location of the origin of one type of rough burning as discussed above, boundary layer injection of water made possible a striking demonstration of the effect of rough burning on efficiency and thrust. By this technique it was possible to control the transition from rough to smooth burning in a given burner keeping all other variables constant. Table 1 summarizes the results of several experiments. Data for carbon tetrachloride are included to show that the mere increase in mass flow due to injection was not responsible for the apparent increases in thrust and efficiency. An inspection of the table makes obvious why rough burning should be avoided at all costs in a practical operating burner even if structure and flame failure could be avoided. Operating efficiencies are

TABLE I

INFLUENCE OF INJECTION ON BURNER EFFICIENCY

Run	M_a lb/sec	T_2 °F	P_2 psig	ϕ	Fuel	Injectant	Injectant Rate lb/sec	Injectant % total mass	S_a (sec)	η_i
136a	1.18	96	34.0	1.06	heptane	-	-	-	131	77
b	1.15	100	43.9	1.09	"	10% N_aCl	.035	2.7	152	90
c	1.16	100	34.5	1.08	"	-	-	-	132	78
d	1.16	105	33.4	1.08	"	CCl_4	.044	3.4	130	77
152b	1.19	88	34.5	1.02	pentane	-	-	-	118	69
a	1.19	88	48.7	1.02	"	water	.049	4.1	153	90
h	1.19	88	37.5	1.02	"	-	-	-	123	72
g	1.19	88	51.5	1.02	"	20% KCl	.030	2.5	160	94

decreased as much as 20% at the onset of the instability.

As mentioned above, concomitant with the study of boundary layer injection, the equipment for measuring the amplitude and frequency of the pressure fluctuations in the burner was developed and introduced. This equipment permitted for the first time the possibility of some quantitative differentiation between types of rough burning. As might be inferred from the above discussion, it was early recognized that there was probably more than one type of instability, but no means were available for accurately describing the several varieties. There were audible differences in that the observer could distinguish different noises, but it was impossible to define them accurately. A typical example of the type of record obtained with this equipment has been shown in Figure 7. The type of roughness shown in this particular record, i.e. before the injection of water, appeared to have a frequency of the order of 45 to 50 cycles per second and was accompanied by pressure fluctuations as high as 30 to 40 pounds per square inch. To be sure, the fluctuations were frequently somewhat aperiodic, but it was possible to assign average frequencies and amplitudes to the phenomenon. This general type of record was invariably obtained at some time when the type of roughness which has been discussed so far was encountered. In order to characterize this type it is in order to list the conditions and symptoms which seemed to accompany its appearance. These are:

1. It occurred largely with a "poor igniter." Most of the work described above was done with a simple 0.75 inch oxyhydrogen cone.

2. It was accompanied by the appearance of flames, i.e. detonations, upstream from the igniter.

3. It could be eliminated by boundary layer injection of water or salt solutions.

4. It was associated with rather large pressure fluctuations, i.e. up to 50 pounds per square inch.

5. The frequency of the pressure fluctuations was generally of the order of 35 to 60 cycles per second.

The first four of these characteristics are more or less consistent with the hypothesis mentioned previously, namely that the roughness was due to repetitive backfires arising from detonations starting at the junction of the flame front with the duct wall by virtue of pockets of air-fuel mixture activated by the pilot flame but not sufficiently ignited to be immediately burned. It is of interest, therefore, to examine whether the frequency of the pressure fluctuations can also be accounted for by this concept. The following simple hypothesis is presented for consideration.

In order to arrive at a number for the frequency which should be observed, the following picture of the cycle is assumed:

1. The detonation begins at the intersection of the flame front with the duct wall and travels upstream a distance in general from one to three feet.

2. At the expiration of the detonation, fresh air-fuel mixture flows back at the average stream velocity to replace that consumed by the detonation.

Obviously, the minimum time interval between detonations must be the sum of the times required for these two steps in the cycle, the frequency then being the inverse of this time interval. With respect to the time required for step 1, it will be recalled that the velocity of the detonation increased as it traveled upstream. However, from the data gained at two locations (8) it is found that the following equation roughly approximates the observed velocities with respect to the duct wall:

$$v = v_o + 350\, x^2$$

provided v_o, the initial velocity, is small with respect to the later velocities and where x is the distance upstream from the junction of the flame front with the duct wall, ca. 0.75 feet downstream from the igniter. Upon integration, this equation leads to

$$t - t_o = \frac{1}{\sqrt{350v_o}} \quad \text{arc tan}\left(x \sqrt{\frac{350}{v_o}} \right)$$

In order to solve this equation it becomes necessary to assign values to v_o, the initial velocity, and to x, the total distance traveled. On the basis of the observed angles of the flame front from the simple 0.75" oxy-hydrogen cone igniter, it appears that the "normal" flame velocity in the burner is of the order of 20 to 30 feet per second. Moreover, as will be discussed later, there is a residual pressure fluctuation of one to two pounds per square inch in the burner due probably to an organ pipe type of resonance. It turns out that this fluctuation can account for a periodic velocity component upstream of as much as 50 feet per second. Near the wall an upstream component of this magnitude could actually bring a portion of the stream to rest relative to the wall. Consequently, making the reasonable assumption that the detonation starts out as an ordinary flame, it would appear that v_o above could have a value of the normal flame velocity in the duct or 20 to 30 feet per second relative to the wall.

With respect to the value of x, it was pointed out above that observation by means of a glass section, substantiated by measurements with the probes, indicated that the detonations traveled anywhere from 4 to 30 inches upstream from the igniter which corresponds to a total distance of roughly 1 to 3 feet assuming as a starting point 8 inches downstream from the igniter. Table II shows the frequencies calculated from the equation above assuming initial velocities, v_{o_1}, of 10, 20, and 30 feet per second together with distances, x_1, of 1, 2, and 3 feet. Also, it was assumed that the average stream velocity, which determines the time for the second portion of the cycle, was 250 ft./sec. This is within 10% of the true value for all S_a's above about 125 (16).

TABLE II

v_o fps	x = 1 ft.	x = 2 ft.	x = 3 ft.
10	36	30	27
20	50	40	34
30	60	45	38

In view of the fact that observed frequencies have been from 35 to 60 cycles per second, the agreement seems reasonable. Although this agreement does not comprise proof of the hypothesis, it does support the consistency of the assumptions which have been made and the conclusions drawn therefrom.

PART II

MORE RECENT RESULTS

The results discussed up to this point comprise a coagulation of more or less random observations over a considerable period of time. The concepts developed above appeared to explain to a large extent the causes of the most serious type of rough burning. Moreover, they suggested that the remedy was to be found in "good" igniters. Although examination of the pressure fluctuation records indicated that other types of instability might exist occasionally, they did not appear to present serious obstacles to good burning, especially since smooth burning was almost invariably obtained when a "good" igniter, e.g. 1-226AB, was used. Consequently, because of an interest in the study of various factors on over-all burner performance (16), no immediate further investigation of rough burning was contemplated.

However, in conjunction with the careful study of the effect of various burner variables on performance, it was decided to eliminate any possible variation due to the distribution of fuel in the air stream. Measurements of the fuel concentration across the duct at the igniter indicated a lack of homogeneity with the injectors which had been used. Consequently, an investigation of injectors was launched which culminated in the discovery that even with the best known burner configurations rough burning resulted with certain injectors. This phenomenon was finally traced to the pressure drop through the injectors (7). That is to say, it was found that a fuel injector which required a high pressure in order to supply sufficient fuel invariably resulted in smooth burning with Igniter 1-226AB whereas an injector which required only a low pressure resulted in pressure fluctuations of the order of 20 to 30 cycles per second with an amplitude as high as 10 to 12 pounds per square inch. The possibility of this sort of coupling resonance had been previously recognized by others (1).

The above observation precipitated a decision to make a comprehensive study of the effect of all the known variables on rough burning. Accordingly, a long series of runs was made in which all possible combinations of two igniters, two tailpipe lengths, two inlet air humidities, three fuels, and three fuel injectors were tried. As described previously (16), a run comprised determining the air specific impulse as a function of equivalence ratio over a range of the latter from 0.3 to 1.4, usually at intervals of about 0.1. A record of the pressure fluctuation was taken at each point.

The two igniters used were 1-2 and 1-226AB. The tailpipe lengths were 14 and 18 inches respectively. The fuels were pentane, heptane, and kerosene. The humidities were about 0.01 and 0.025 lbs. of water per lb. of dry air.

The three fuel injectors were all variations of 1-354 which comprised essentially eight injection needles terminating in an annular orifice as shown in Figure 2. The only differences between the three consisted in the size of the holes in the needles and consequently in the pressure drops through them. Figure 10 shows pressure drop as a function of fuel flow for each injector.

The resulting mass of data was considerable and it is not worthwhile to reproduce it all here in either tables or graphs. Instead, the significant data will be summarized. As a matter of record, Table III shows the data recorded for a typical run and Figure 11 shows sample traces of representative types of instability as obtained from the pressure-fluctuation recording equipment. In connection with the latter, it should be pointed out that this method of measuring amplitudes and frequencies is not ideal especially for determining the latter. At best there is considerable labor involved in counting the peaks from several sections of the tape in order to obtain average or representative values. In addition, there is often superposition of one frequency on another which makes resolution difficult and largely a matter of judgement upon the part of the observer. For example, Figure 11A shows a predominant frequency of about 20 cps, but closer examination shows a superimposed frequency of much smaller amplitude of about 125 cps. A frequency analyzer would be much more satisfactory for this purpose. Nevertheless, it is felt that trends and ranges of values reported here are reasonably correct and reliable. Another point worthy of note is that the recording equipment used was not adapted to frequencies above 150 cycles per second. However, as a check to determine whether there were frequencies any higher than 150 which might be significant, some experiments were made using a Brush crystal pickup in conjunction with a cathode ray oscilloscope. Above

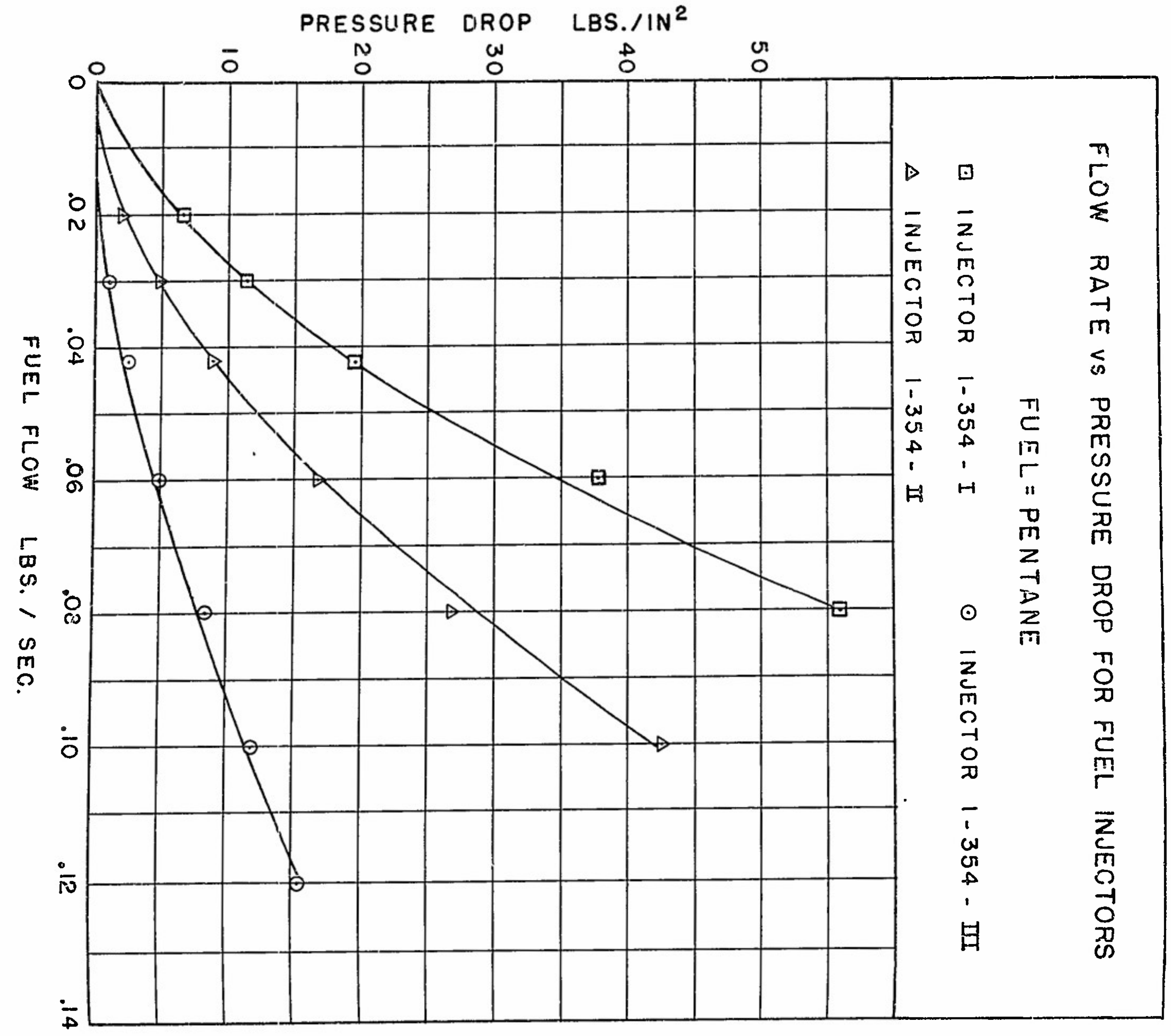


FIGURE 10

TABLE III

TYPICAL RUN DATA FOR ROUGH BURNING STUDY

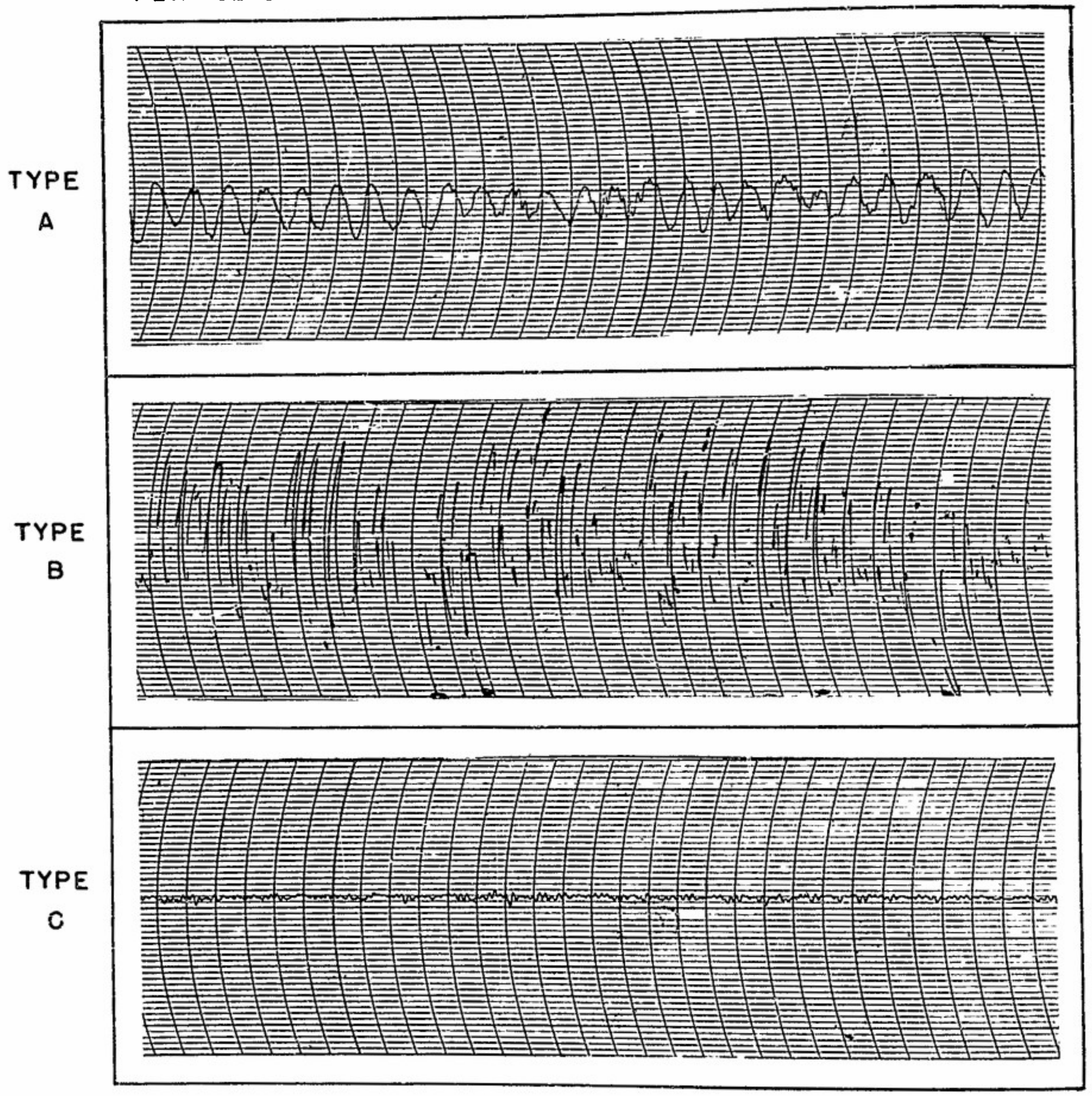
Run #	Fuel	Fuel Injector	Igniter	Tailpipe Length Inches	m_a-air mass flow lb/sec	m_f-fuel mass flow lb/sec	ϕ-equivalence ratio	T_{s_1}-inlet air temp. °F	p_2-flame pressure psig	$q_2 - 1/2\rho_2 V_2^2$ psi	$\bar{V}_2$-stream velocity ft/sec	H_2O-humidity lb/lb air	S_a-air specific impulse $(sec)^{-1}$	η_I-impulse efficiency %	Δp-aver. p_2 fluct, psi	f - frequency Δp cps
253a	pentane	II	1-226AB	14	1.22	0.031	0.38	223	16.5	3.2	450	.009	81	73	5	5
b	"	"	"	"	1.22	0.039	0.49	223	19.0	2.9	410	"	86	71	8(4)	12(24)
c	"	"	"	"	1.22	0.048	0.60	225	23.0	2.8	385	"	95	67	5	23
d	"	"	"	"	1.21	0.053	0.68	225	27.0	2.6	368	"	104	70	3(1)	20(80)
e	"	"	"	"	1.20	0.058	0.74	225	31.0	2.3	318	"	113	73	7(.5)	21(105)
f	"	"	"	"	1.23	0.062	0.77	226	36.0	2.0	275	"	121	78	8(.5)	21(105)
g	"	"	"	"	1.17	0.063	0.82	227	43.0	1.8	252	"	142	90	2(.5)	20(110)
h	"	"	"	"	1.15	0.068	0.90	227	45.7	1.7	252	"	151	92	.5	110
i	"	"	"	"	1.15	0.075	1.00	"	47.8	1.7	240	"	156	92	.5	120
j	"	"	"	"	1.15	0.078	1.03	"	48.2	1.7	238	"	157	93	.5	120
k	"	"	"	"	1.15	0.083	1.10	"	48.2	1.6	238	"	157	93	.5	120
l	"	"	"	"	1.16	0.088	1.16	"	46.8	1.7	240	"	152	89	.5	120
m	"	"	"	"	1.18	0.093	1.22	"	44.8	1.8	257	"	146	85	.5	115

N.B. - In last two columns the presence of a second major fluctuation is indicated by parentheses around the corresponding values of frequency and amplitude.

TYPICAL SAMPLES OF PRESSURE FLUCTUATION RECORDS

CHART SPEED = 125 MM./SEC.
PEN SENSITIVITY ~ 1 PSI/MM.

INLET AIR TEMP. = 228 ± 3°F.
FUEL = PENTANE



	RUN	IGNITER	INJECTOR	TAIL-PIPE	P_2 psig	S_a	ϕ	Δp FREQ. cps	Δp AMP. psi
A	253 f	1-226AB	II	14"	36	121	.77	20	4-9
B	486 d	1-2	III	18"	30	124	1.02	50	15-40
C	253 l	1-226AB	II	14"	47.8	156	1.00	115	1-2

FIGURE 11

150 cycles per second no appreciable amplitudes were observable except at 8 to 10 kilocycles. These were very small and probably can be interpreted as "noise."

There follows a discussion of each of the three types of rough burning pressure fluctuations which were noted during the course of the investigation. These types are characterized primarily by their frequencies which were of the order 20 to 30, 35 to 60, and 100 to 130 cycles per second respectively. These will be called A, B, and C in order of increasing frequency. In each case the effect of the controlled variables will be discussed and an attempt will be made to elucidate a mechamism accounting for the occurrence of the instability.

Type B Pressure Fluctuations - Frequency range: 35 to 60 cps

Discussion of this type comes first because it has already been largely covered under the section on early work. It was found that its occurrence was largely confined to the case of Igniter 1-2 which confirms the earlier conclusion that one kind of rough burning is due to poor ignition. As before, it was accompanied by burning upstream from the igniter. However, there was a significant difference between this type as observed in the more recent work compared with earlier observations. The amplitude was in general greater and the igniter and duct upstream therefrom rapidly became red hot. If permitted to continue, the igniter was burned up. In the early work the roughness could be permitted to continue for some time without damage. Moreover, it was observed that the occurrence of this type was confined to fairly sharply defined and reproducible ranges of equivalence ratio, namely 0.95 to about 1.25. This is also in contradistinction to early experience where detonation occurred at equivalence ratios as low as 0.7, but is in accord with other observers, e.g. Fenning (9), who have noted that the tendency of hydrocarbon air mixtures to detonate is much greater in the rich range. These differences are doubtless due to the fact that in the early work with the fuel injectors then used the distribution of fuel in the air stream was not homogeneous. Since detonation is even more sensitive to mixture composition than ordinary burning, it is reasonable to expect that only certain portions of the stream could propagate a detonation so that its occurrence should have been more spotty and irregular depending upon the pattern of air-fuel distribution. In fact, the irregular nature of the detonations could be readily observed in the pictures mentioned previously. Sometimes the whole duct would be apparently filled with flame. Frequently, however, tongues of incandescence would burst into the field of view occupying only a small proportion of the duct cross section. In the more recent results, on the other hand, the fuel injectors all provided a perfectly homogeneous mixture upstream from the pilot with the notable exception of kerosene which was incompletely vaporized. Thus, not only were the mixture conditions for propagation of the detonation more reproducible, but when they occurred the entire stream was involved so that the heat liberated was greater resulting in incandescence of the wall and destruction of the pilot. Also the amplitudes of the pressure variation were greater which is consistent with the better homogeneity. It was mentioned that kerosene was not completely vaporized. The fact that no tendency to rough burning of the type under consideration was encountered in the case of this fuel is strong evidence in support of the explanations and concepts which have been developed above.

In passing, it should also be pointed out that the humidity and tailpipe length as well as the pressure drop across the fuel injector had no determinable influence on the properties of this type of instability. The primary controlling factors were the igniter efficiency and the equivalence ratio.

Type C Pressure Fluctuations - Frequency range: 100-120 cps

It is somewhat questionable as to whether the pressure fluctuations observed in this frequency range should be considered as a form of burner instability. They seemed to be relatively unaffected by any of the variables mentioned and were common to all combinations of igniter, fuel, humidity, tailpipe length and fuel injector. Furthermore, specific experiments showed that boundary layer injection of water had no effect on the pressure fluctuations in this frequency range. They were even detectable under conditions of no burning, i.e. cold flow, although the amplitudes were only about half a pound under these conditions. Since under some conditions, however, the amplitudes were as large as 9 to 12 pounds per square inch, and since their presence at all times might serve to stimulate or trigger other instabilities, it appeared expedient to consider them in the present discussion. Typical examples are shown in Figure 12.

The relative independence of the frequency of this type of pressure fluctuation with respect to all the variables under examination immediately indicated that it might be a property of the geometry of the duct system as a whole. An analysis of resonance phenomena in a 4 inch burner by Shaffer (21) had succeeded in correlating frequency with the length of the duct in terms of a fundamental resonance phenomenon under the flow conditions obtaining. Accordingly, an attempt was made with some success to apply his reasoning. A similar analysis has also been reported by Topps and Probert (23).

Shaffer shows that standing waves can be formed in a gas stream flowing with velocity $\overline{V}$ through a tube and that they obey the following modified equation

$$f = c(1 - M^2)/\lambda$$

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SAMPLES OF TYPE "C" PRESSURE FLUCTUATIONS

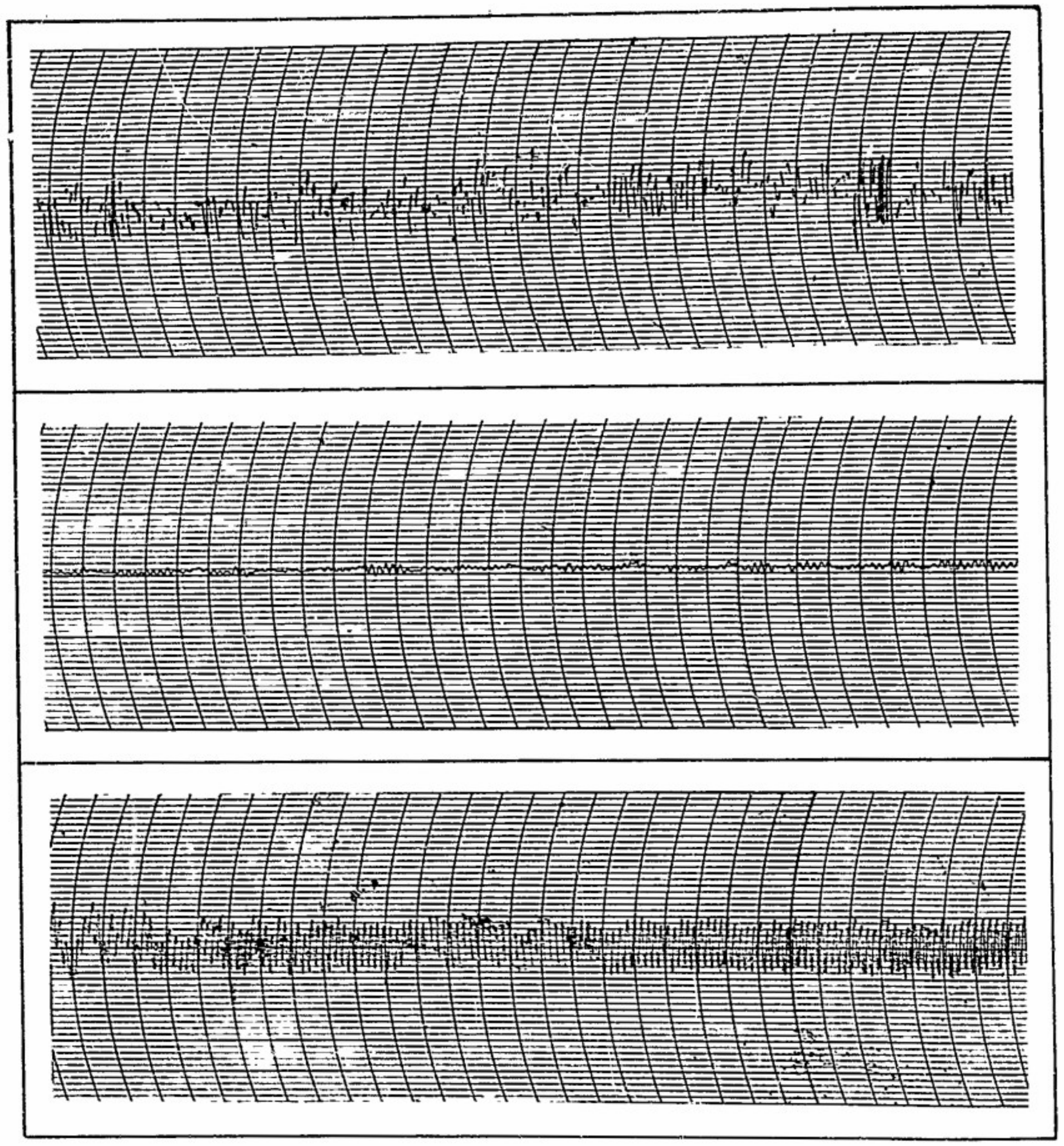
CHART SPEED = 125 MM./ SEC.
TAILPIPE = 14"

INLET AIR TEMP. = 240±20°F.
Δ FREQ. ≈ 120 cps

a

b

c



	RUN	IGNITER	IN-JECTOR	FUEL	P_2 psig	S_a	ϕ	PEN SENSITIVITY psi / mm.	Δp AMP. psi
a	COLD FLOW	—	—	—	—	—	—	0.1	.5
b	275e	1-226AB	I	KEROSENE	34.7	127	1.10	1.0	1-2
c	227f	1-2	III	PENTANE	24.5	100	1.28	1.0	8-10

FIGURE 12

where λ is the wave length, M is the local Mach number, f is the frequency, and c is the velocity of sound. The wave length, λ , is 2L for a tube open or closed at both ends and 4L for a tube open at one end only where L is the length of the tube. In the burners under discussion, since the temperature upstream from the igniter was in general within a few degrees of 240°F., a value of 1280 feet per second can be taken for the sonic velocity, c. The velocity, $\overline{V}$, is determined from air specific impulse in accordance with the relationship previously determined (16). Incidentally, the values of these variables are taken in terms of the inlet stream, i.e. upstream from the burning zone, because by far the greater effective length of duct precedes the igniter. With respect to L, it is apparent from Figure 1 that the maximum value from the fuel injector to the end of the tailpipe is 70 inches in the case of an 18 inch tailpipe or about 5.8 feet. In view of the fact that the effect of burning in the last few inches of the duct is to decrease the value of L, a minimum value of 5 feet can be assumed. The following table summarizes frequencies calculated from equation (2) above:

TABLE IV

S_a	$\overline{V}_2$	Frequency cycles per second L = 5.8 ft.	L = 5.0 ft.
80	440	97	113
100	350	102	118
120	280	105	122
140	235	106	124
160	225	107	124

Since the fuel injector effectively blocks a large portion of the duct cross section and since choking obtains at the exhaust for all values of S_a above 80, it was considered that the duct was effectively closed at both ends and that λ was therefore equal to 2 L. In Figure 13 are plotted all the data points in this frequency for all the runs made. The two curves represent the calculated frequencies for the minimum and maximum values of L. Although there is considerable scatter, the correlation is reasonable. More than half of the total number of points fall within the theoretical curves. Probably one of the major reasons for the scatter is the inadequacy of the method used for determining frequency by counting peaks in sections of the oscillograph trace mentioned above. Moreover, the experimental points represent values taken on both the rich and lean sides of stoichiometric mixtures and no allowance has been made for the effect of the fuel on the properties of the stream.

An obvious way to check the consistency of the above explanation for the pressure fluctuations in this frequency range is to increase the value of L by putting more duct between the fuel injector and the igniter. Accordingly, two runs were carried out in which the distance between the fuel injector was increased from 52 inches to 82 inches resulting in upper and lower limits for L of 8.3 and 7.5 feet respectively. Under these conditions, frequencies calculated by the method discussed above cover the range from 65 to 75 cycles per second. All of the observed frequencies were between 60 and 80 cycles per second with the bulk of them occurring at 70 cycles per second. It would appear, therefore, that the pressure fluctuations associated with Type C instability are reasonably interpretable in terms of a fundamental frequency associated with the duct length.

Type A Pressure Fluctuations - Frequency range: 20-30 cps

It has already been indicated that the pressure fluctuations in this frequency range have been associated with a coupling between the fuel injection system and the burner. It had been observed that if the fuel injection rate was made constant and independent of pressure changes in the burner, this low

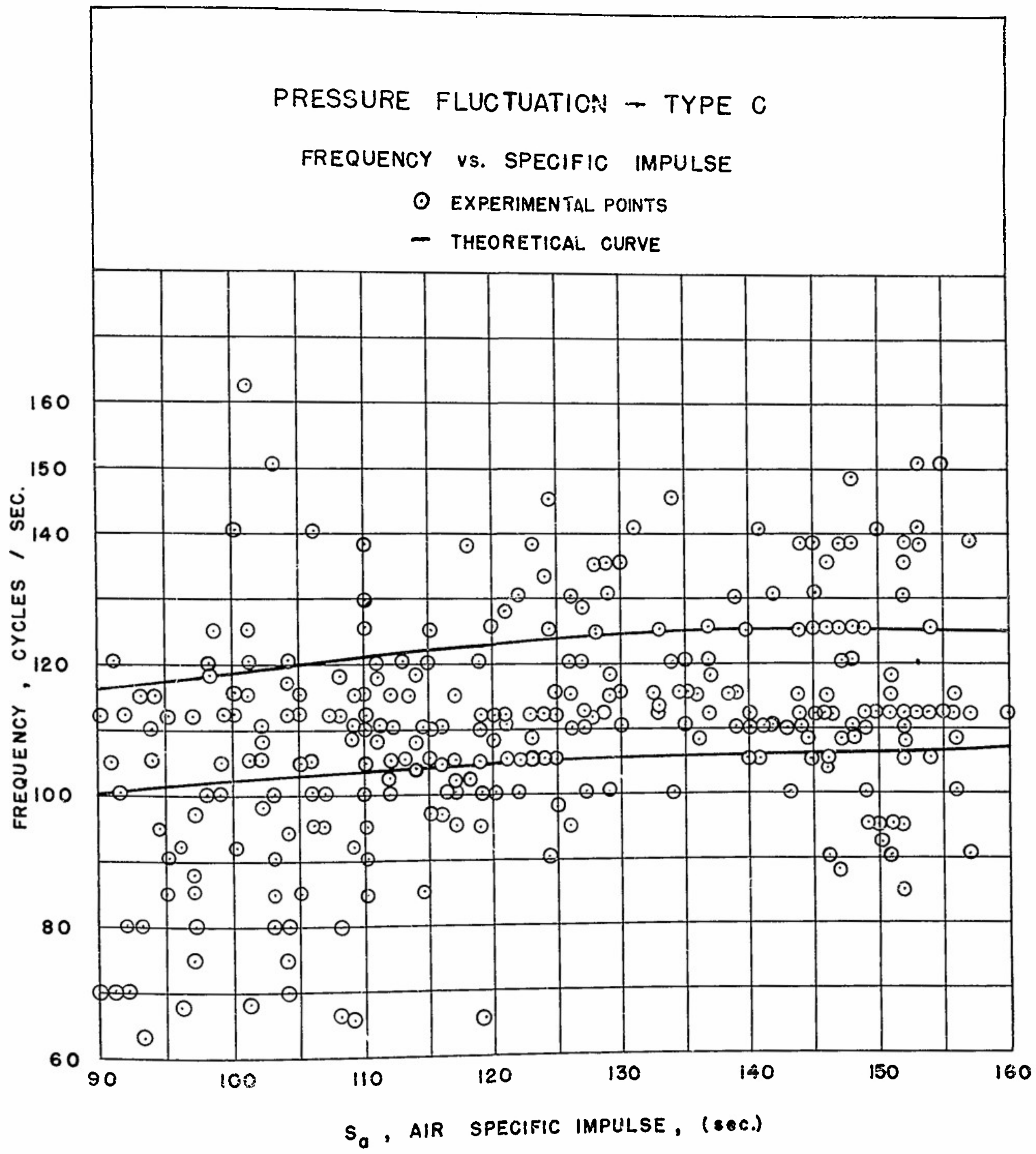


FIGURE 13

frequency pulsation was eliminated. In the early experiments this shielding of the fuel injection rate from burner pressure fluctuations was accomplished both by insertion of a sonic orifice between the fuel injector and the burner and by "pinching" the ends of the fuel injector needles so as to maintain a high pressure drop in the fuel stream. As already noted, the present investigation was carried out with three fuel injectors identical except for the pressure drop imposed on the fuel flow. The results obtained were consistent with the supposition in that Injector III with the lowest pressure drop was most prone to pulsation over the widest range of equivalence ratio. Injector I, with the highest pressure drop, showed little tendency to pulsation except at the lowest equivalence ratios, i.e. very low fuel flows. Injector II was intermediate in performance. Moreover, the fluctuations were invariably most noticeable in the equivalence ratio range where the rate of change of burner pressure with equivalence ratio was highest, i.e. between 0.6 and 0.9 and between 1.1 and 1.4. Figure 14 shows a typical curve for burner pressure as a function of equivalence ratio. No effect was noted upon pressure fluctuations of this low frequency for changes in humidity, igniter, or tailpipe length. Also varying the fuel from pentane to heptane had no effect. However, there was a definite difference in the case of kerosene which will be discussed later.

In predicting the frequencies which should occur for the pressure fluctuation due to the fuel injector, the following considerations were entertained. Assume an arbitrary pressure pulse arising from some cause. Upon reaching the fuel injector this pulse results in a slight temporary decrease in fuel flow causing a decrease in equivalence ratio in the portion of stream passing the injector at the time of the pulse. When this portion of lean mixture reaches the igniter, the pressure level in the burner drops. The resulting negative

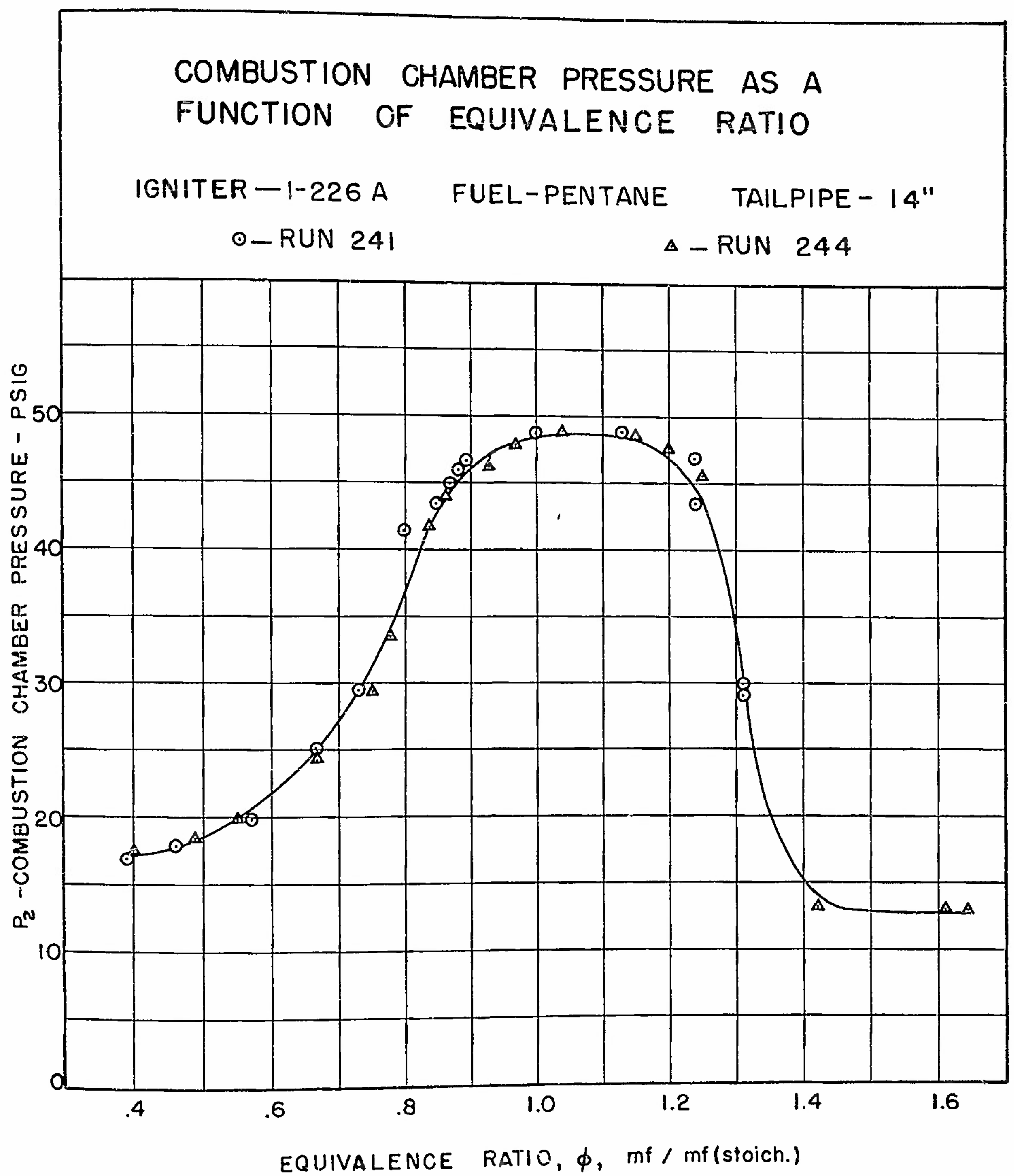


FIGURE 14

pressure "pulse" then travels upstream causing an increase in the fuel flow. The resulting increase in equivalence ratio brings about an increase in burner pressure when it reaches the igniter and the cycle repeats. It is assumed that the pressure pulse travels upstream at a velocity with respect to the duct equivalent to the sonic velocity minus the average stream velocity. The change in equivalence ratio, on the other hand, travels from the injector to the igniter at the average stream velocity. The time required for one complete cycle is thus twice the sum of the times required for the pulse to go from the igniter to the injector and the change in equivalence ratio to go from the injector back to the igniter. This relationship can be expressed by the following equation for frequency, f,

$$f = \left[2\left(\frac{d}{v} + \frac{d}{c-v} \right) \right]^{-1}$$

where c, the sonic velocity, is 1280 feet per second, $\overline{V}$ is the stream velocity and depends upon the air specific impulse as described before, and d is the distance in feet from the igniter to the injector. Actually, although the distance from the injector to the igniter was 52 inches, it is quite likely that a change in equivalence ratio would not bring about a change in burner pressure until it had reached well into the combustion zone, probably about 8 inches downstream from the igniter. Consequently, a convenient value for d is 5.0 feet. The following table summarizes the frequencies which should be observed according to the equation at various air specific impulses.

TABLE V

S_a	V ft. per sec.	f cycles per sec.
80	440	30
100	350	25
120	280	22
140	235	21
160	225	20

Figure 15 shows a plot of the frequencies observed during the course of this investigation as a function of air specific impulse. Again the curve represents the values from the table. Above a specific impulse of 90 the agreement is fairly good. At lower specific impulse values, however, there is a considerable amount of data indicating frequencies of the order of 6 to 15 cycles per second. No explanation of these has been achieved as yet. It is noteworthy, however, that below a specific impulse of about 90 choking occurs at the fuel injector so that fuel flow should be uneffected by pressure fluctuations. Consequently, the very low frequency pulsations shown on the graph are probably not due to variations in fuel flow caused by pressure fluctuations in the burner.

In the analysis above consideration was given to the effect of a pressure pulse at equivalence ratios below stoichiometric. Over in the rich region, however, an increase in pressure resulting in a decrease in fuel flow would bring about a further increase in pressure because of the rapidly decreasing flame pressure with increased equivalence ratio. Similarly a "negative" pressure pulse or a decrease in burner pressure would tend to increase fuel flow and result in a further pressure decrease. Thus, regeneration and amplification of the initial pressure pulse is possible. It would be expected, of course, that this regeneration should show up most strongly with the injector having the lowest pressure drop as is indeed the case. Since this phenomenon can occur only in the rich region where the fuel flow is large, the pressure drops through the two higher pressure injectors are already too great to make the fuel flow through them sensitive to burner pressure variation. In the case of Injector III, however, it was found almost impossible to avoid vigorous pressure fluctuations finally resulting in blow off at equivalence ratios beyond 1.1 which is the point where further

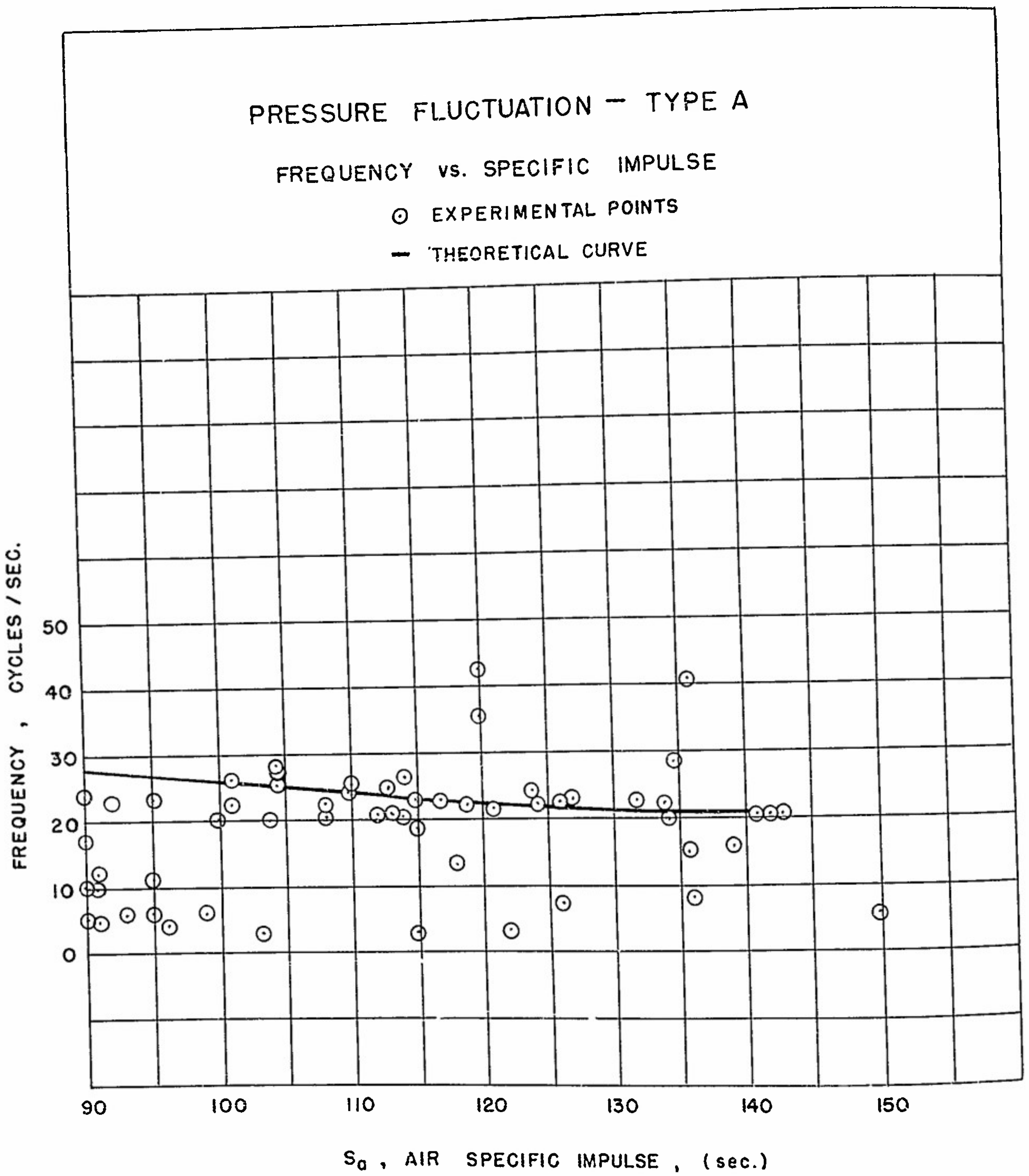


FIGURE 15

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increase in fuel flow results in a rapid decrease in burner pressure. The interesting exception consisted in the behaviour of kerosene. With this fuel and Injector III it was possible to keep the burner ignited up to an equivalence ratio of 1.6 or more. As was pointed out in an earlier communication (16), probably because of incomplete vaporization the combustion level, and therefore the burner pressure, does not decrease in the rich region with this fuel but remains relatively constant beyond the stoichiometric point. It is, therefore, quite consistent with the picture developed above that regenerative pressure fluctuations culminating in blow off should not occur with kerosene.

It is of interest to consider another possibility in connection with the ultimate result of initial pressure fluctuations in the rich region. Since on the rich side a positive pressure pulse results in a second positive pressure pulse and a negative pulse results in a negative pulse, the cycle from one pressure peak to the next involves only one "round trip" from the igniter to the injector as opposed to two in the case of mixtures leaner than stoichiometric. Consequently, the apparent frequency of the pulsations should be twice that of the fluctuations on the lean side. While it is difficult to observe this because of the tendency to blowoff, it is occasionally possible to pick up frequencies of this order of magnitude. Figure 16 shows two such samples of oscillograph record. These occurred at equivalence ratios just beyond stoichiometric. In one case blowoff occurred very quickly, in the other the fluctuations were relatively small and persisted for some seconds. For comparison, a typical sample of fluctuations due to the fuel injector taken with the same burner but in the lean region is included. It will be noted that the observed and calculated frequencies agree quite closely.

Since the frequency of pressure fluctuations due to pulsing of fuel flow

SAMPLES OF TYPE "A" PRESSURE FLUCTUATIONS

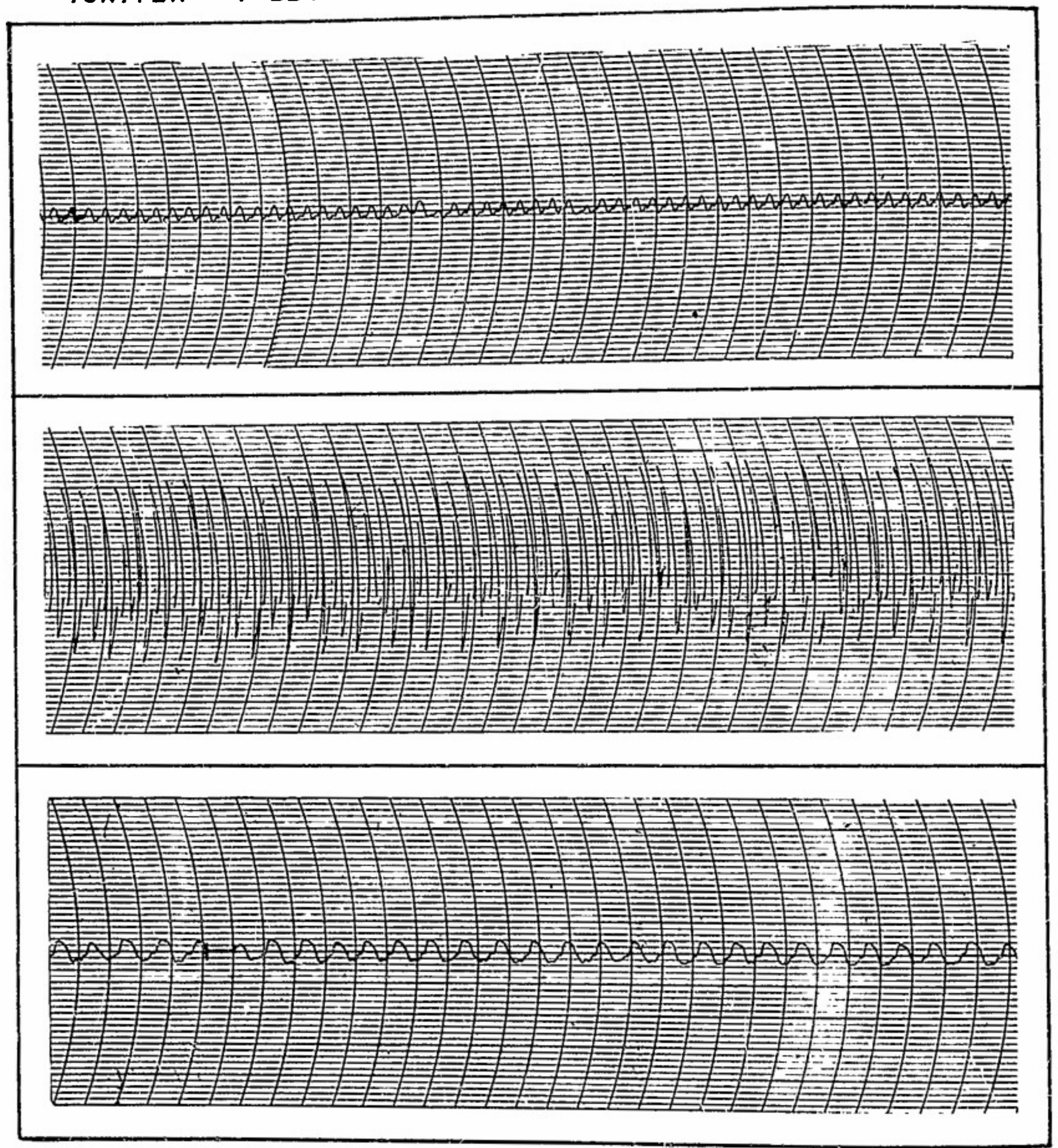
CHART SPEED = 125 MM./ SEC.
TAILPIPE = 14"
IGNITER = 1-226 AB

INLET AIR TEMP. = 238 ° F.
FUEL = PENTANE
INJECTOR = III

a

b

c



	RUN	P_2 psig	S_a	ϕ	PEN SENSITIVITY psi / m.m.	Δ_p AMP. psi	Δ_p FREQ. OBS. cps	Δ_p FREQ. CALC. cps
a	449i	29.8	106	1.04	2	4 - 6	46	48
b	449f	32.0	128	1.10	2	40 - 50	45	44
c	449d	26.5	100	0.60	1	3	23	25

NOTE: above (b) data not too reliable due to large fluctuations in gage readings

FIGURE 16

is directly dependent upon the distance between the igniter and the fuel injector, it should be possible to check the above hypothesis by increasing this distance and noting the effect on frequency. This was actually accomplished in connection with determining the effect of length on Type C instability discussed above. The distance from the fuel injector to the igniter was increased from 52 inches to 82 inches. Assuming as before an additional 8 inches beyond the igniter before the change in equivalence ratio is reflected in a pressure variation, a value of 7.5 feet can be taken for d in equation above. The following table compares calculated and observed frequencies under these conditions:

TABLE VI

S_a	Frequency cps Observed	Frequency cps Calculated
106	14-15	16
109	14-15	16
111	13-14	15
119	13	15

These measurements were made with Injector III. In this particular run the subject frequency range could not be detected at the next highest S_a which was 149, probably because this value is in the region where burner pressure does not vary appreciably with equivalence ratio. On the rich side of stoichiometric blowoff persisted.

Another experiment of interest in connection with pressure fluctuations due to the fuel injector consisted in chopping the fuel flow by means of a motor driven rotary valve. Injector I, which was least subject to flow fluctuation from pressure changes, was used together with Igniter 1-226A and a 14 inch tailpipe. The frequency of chopping was matched identically by the frequency of pressure fluctuation in the burner throughout the range tested which was from 36 to 92 cycles per second. Thus the assumption that fluctuations in fuel flow can account for pressure fluctuations in the frequency range under consideration appears to be valid.

It is perhaps worthwhile speculating at this point. It was noted above that the difference in amplitude between the pressure fluctuations associated with the length of duct for cold and hot flow could not be immediately accounted for. However, it is appa ent that the coupling between the fuel injector and the burner might well act as an amplifier so that the initial amplitude of the duct tone could be increased by interaction with the fuel injector, thus providing larger amplitudes under burning conditions. In this connection it is noteworthy that in general the amplitude of the pressure fluctuations in the range 100 to 120 cycles per second was somewhat larger with Injector III than with Injector II (c.f. Figure 12). It is also interesting to consider the possibility of using a ducted burner of the type herein discussed as an audio amplifier by means of modulating the fuel flow. If the frequency response of the burning process to changes in fuel flow is sufficiently high, it would seem that amplification factors of considerable magnitude might be obtainable over a useful range.

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DATE	U.S. CLASS.	COUNTRY	LANGUAGE	PAGES	ILLUSTRATIONS
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